ARTICLE COMPRISING A TUNABLE FILTER

Field of the Invention

The present invention relates to optical communications. More particularly, the present invention relates to a tunable filter for use in conjunction with optical communications systems.

Background of the Invention

FIG. 1a depicts a simplified schematic diagram of a typical WDM network **100** in the prior art. WDM network **100** includes a plurality of transmitters **TX-1** through **TX-*n***. Each of the transmitters includes an optical source for generating an optical signal **λ-*i***, ***i*** = **1**, ***n***. Each optical signal **λ-*i*** is characterized by a unique peak wavelength onto which information may be modulated in well-known fashion. The plurality of optical signals **λ-1** through **λ-*n*** are combined into a single "multiplexed" signal ***m*-λ** by wavelength multiplexer **102**, and the multiplexed signal ***m*-λ** is then launched into optical fiber **104**.

A plurality of subscriber terminals (*e.g.*, **106-*S*1**, **106-*S*2** and **108-*S*1** through **108-*Sn***) are in optical communication with network **100**. Each such subscriber terminal includes a receiver(s) (not shown) for receiving information that is carried over network **100** via multiplexed signal ***m*-λ**. An individual subscriber terminal may subscribe to the information contained on only a single channel (*i.e.*, on a single optical signal **λ-*i***) of multiplexed signal ***m*-λ**.

Subscriber terminals **108-*S*1** through **108-*Sn*** located at end terminal **108** require, collectively, most or all of the individual channels **λ-1** through **λ-*n*** multiplexed signal ***m*-λ**. To provide such channels to subscriber terminals **108-*S*1** through **108-*Sn***, multiplexed signal ***m*-λ** is typically demultiplexed, fully resolving it into its constituent channels. Demultiplexer **110** is used for that purpose.

Subscriber terminals **106-*S*1** and **106-*S*2** are located at "small" intermediate node **106**. Node **106** requires only a few of the channels of multiplexed signal ***m*-λ** (*i.e.*, terminal **106-*S*1** receives only channel **λ-1** and terminal **106-*S*2** receives only channel **λ-3**). As a consequence, rather than fully demultiplexing multiplexed signal ***m*-λ** at node **106**, only the required channels

are dropped (*i.e.*, removed or separated) from multiplexed signal ***m-λ*** and delivered to the appropriate subscriber terminal. One or more "wavelength "(add)/drop" filters (*i.e.*, filters **106-*WAD*1**, **106-*WAD*2**), which are operable to drop a single channel, are advantageously used for this purpose.

For example, in network **100** at node **106**, add-drop filter **106-*WAD*1** separates and drops channel **λ-1** from multiplexed signal ***m-λ***. Channel **λ-1** is then transmitted to subscriber terminal **106-*S*1**. Also, add-drop filter **106-*WAD*2** separates and drops channel **λ-3**, which is then transmitted to subscriber terminal **106-*S*2.** As the name implies, in at least some embodiments, wavelength add-drop filters are operable to add a single channel having the same characteristic wavelength as the drop channel. For example, in network **100**, transmitter **106-*T*1** generates signal **λ-1** that is added to multiplexed signal ***m-λ*** via **106-*WAD*1**. Alternatively, such a channel may be added to the multiplexed signal elsewhere in network **100**.

It will be clear to those skilled in the art that a typical WDM optical communications network will have many more nodes and typically includes many other elements (*e.g.*, amplifiers for maintaining signal strength, *etc.*) than are depicted in FIG. 1a. These other nodes and other elements are not shown so that attention can be focused on those elements that are germane to an understanding of the present invention.

FIG. 1b depicts a known wavelength add-drop filter. The particular filter depicted in FIG. 1b is a Fabry-Perot etalon filter, well known in the art. Etalon filter **150** consists of a pair of highly reflective dielectric mirrors ***M*1** and ***M*2** that are separated by a precisely defined gap ***G***. An optical cavity **OC** is defined between opposed surfaces **SM1** and **SM2** of the final dielectric layer of each mirror.

A multiple-wavelength signal ***MWS-IN*** from input waveguide (*e.g.*, an optical fiber) ***F-IN*** is collimated by lens ***L*1** and illuminates the mirrors ***M*1** and ***M*2**. Most of wavelengths of signal ***MWS-IN*** are reflected from the filter and couple into output waveguide ***F-OUT***. Signals $D\lambda_1$ - $D\lambda_j$ having a wavelength within a very narrow range or "passband" are, however, transmitted through the mirrors, pass through lens ***L*2,** and couple into drop waveguide ***F-D***. Any signals ***Aλ*** having a wavelength within the narrow pass band of the filter can be delivered to filter **150** from "add" waveguide ***F-A*** and coupled into output waveguide ***F-OUT***.

Performance parameters of the etalon filter **150**, such as reflectivity/transmissibility, passband, center transmission wavelength of the passband and finesse are readily calculable and

are dependent on properties of the optical cavity **OC** (*i.e.*, gap ***G***) and mirror reflectivity and the coupling efficiency into output waveguides.

Returning to illustrative network **100**, to "drop" two channels (*e.g.*, **λ-1** and **λ-3**) from multiplexed signal ***m-λ***, two add-drop switches (*e.g.*, implemented as described above) can be used. Alternatively, it is possible to drop the same two channels using a single "tunable" etalon filter having an adjustable passband "center" wavelength. The "center" wavelength is the predominant wavelength of the passband (hereinafter "center transmission wavelength").

In such tunable etalon filters, one of the two mirrors is typically placed on a translation actuator (*e.g.*, a piezoelectric transducer) that is under electrical control. Moving the actuator changes the size of the gap between the mirrors. Since the gap (size) controls the center transmission wavelength of the filter, moving the actuator changes that center transmission wavelength.

A problem exists, however, with existing tunable filters. As explained above, to change the center transmission wavelength, the size of the gap between the two mirrors is altered. In doing so, the gap will assume a number of intermediate sizes until the desired size is attained. At such intermediate gap sizes, the optical cavity will tune to channels or signals having intervening wavelengths (hereinafter "intervening channels" or "intervening signals"). Such intervening signals will be transmitted by the filter, delivered to the drop fiber and passed to the subscriber terminal rather than to the intended destination. To prevent intervening signals from being delivered to a subscriber terminal in this manner, those signals must be disadvantageously temporarily interrupted while tuning the filter to a new center transmission wavelength.

The art would therefore benefit from a tunable filter that, during tuning, does not disrupt intervening channels.

Summary of the Invention

Some embodiments of the present invention provide a tunable filter without some of the disadvantages of the prior art. In particular, the illustrative embodiment of the present invention is a tunable filter that does not interrupt intervening channels during tuning.

In accordance with the illustrative embodiment of the present invention, a tunable filter includes an optical cavity, a tuning device and a filter-disabling device. The length of the optical

cavity defines the center transmission wavelength of the filter. Other attributes of the optical cavity and the mirrors define the finesse of the filter.

As used herein, the term "**passband**" refers to the range of wavelengths that are transmitted or passed by a filter, the term "**center transmission wavelength**" refers to the predominant or peak wavelength in the passband, and the term "**finesse**" refers to the transmissibility of the filter. The term "finesse" is also properly considered to be a measure of the "sharpness" of the transmission peak of the filter. And, as will be appreciated by those skilled in the art, the term "finesse" also has mathematical definitions (*e.g.*, assuming equal reflectivity mirrors: finesse = $4r / (1-r^2)$, where "r" is the reflectivity of the mirrors). In the context of the present invention, the term "finesse" is intended to refer to the transmissibility of the filter, as will become clear later in this Specification.

The tuning device is operable to change the center transmission wavelength of the tunable filter. The filter-disabling device is operable to temporarily disrupt the finesse or otherwise substantially lower the transmissibility of the optical cavity, thereby preventing the transmission of any wavelengths through the tunable filter. In some embodiments, filter transmissibility is lowered by disrupting the reflectivity (along the optical axis) of at least one of the two mirrors defining an optical cavity.

In accordance with the present teachings, before changing the center transmission wavelength, the filter-disabling device is enabled. Doing so disrupts the finesse of the optical cavity thereby substantially preventing the transmission of any optical signals through the filter. The tuning device is then used to change the center transmission wavelength. Even though the tuning device will tune to undesired intervening channels during the tuning process, the filter will not transmit such intervening channels since the finesse of the optical cavity is disrupted (*i.e.*, the transmissibility of the filter is low). After tuning is complete, the filter-disabling device is defeated and the filter exhibits its desired transmission characteristic (*i.e.*, transmits the desired channel through the filter).

The inventive concept may be implemented in a variety of ways. Several illustrative embodiments are summarized below and described in more detail later in this Specification.

In some embodiments, the optical cavity comprises two spaced-apart mirrors. In a few of those embodiments, one of the mirrors is movable and functions as the tuning device. In particular, moving the movable mirror changes the length of the optical cavity thereby changing the center transmission wavelength of the filter. The movable mirror can be readily implemented

using well-known surface micromachining techniques (*e.g.*, micro-electromechanical systems "MEMS").

In one embodiment, filter-disabling device comprises an arrangement for tilting or rotating one of the mirrors. Tilting a mirror disrupts the finesse of the optical cavity such that the filter becomes reflective of all wavelengths of light.

In other embodiments, the optical cavity is modified wherein one of the two mirrors is "split" into two groups of layers of dielectric material that are separated by a gap. Thus, the filter has two "gaps," a primary gap between the first and the second mirror (tuning device), and an auxiliary gap (filter-disabling device) that divides the layers of the "split" mirror. Both the primary gap and the auxiliary gap are variable. When the auxiliary gap is at a (readily) predetermined size, the finesse of the filter is at a maximum. By appropriately changing the auxiliary gap, the finesse of the filter is disrupted and the filtering function is defeated.

In other embodiments, the filter-disabling device comprises an electrically-switched absorbing, scattering or depolarizing media that is disposed in the optical cavity. By applying a voltage, the optical characteristic of the media can be changed from non-transmissible to transmissible (or visa-versa). The cavity is tuned (*i.e.*, the center transmission wavelength is changed) by changing the length of the optical cavity.

In still other embodiments, an optical cavity incorporates a semiconductor optical amplifier that provides either a zero-loss or highly lossy roundtrip as a function of whether current is flowing through the optical amplifier.

Brief Description of the Drawings

FIG. 1a depicts a simplified schematic diagram of a typical WDM network **100** in the prior art.

FIG. 1b depicts a typical wavelength add-drop filter, which is implemented using a Fabry-Perot etalon.

FIG. 2a depicts a block diagram of a tunable filter in accordance with the present teachings.

FIG. 2b depicts a method in accordance with the illustrated embodiment of the present invention.

FIGS. 3a - 6a depict the operation of a first illustrative embodiment of a tunable filter in accordance with the present teachings.

FIGS. 3b - 6b depict plots showing reflectivity versus wavelength at the various stages of operation depicted in FIGS. 3a – 6a, respectively.

FIGS. 3c – 6c depict plots showing transmissibility versus wavelength at the various stages of operation depicted in FIGS. 3a – 6a, respectively.

FIG. 7 depicts a plan view of a movable, tiltable mirror for use in the first illustrative embodiment of a tunable filter.

FIG. 8 depicts a side view of the movable, tiltable mirror of FIG. 7.

FIGS. 9a – 9c depict the operation of the movable, tiltable mirror of FIGS. 7 and 8.

FIG. 10 depicts a side view of a second illustrative embodiment of a tunable filter in accordance with the present invention.

FIG. 11 depicts an arrangement of layers that comprise the dielectric mirrors of the tunable filter of FIG. 10.

FIG. 12 depicts a side view of a third illustrative embodiment of a tunable filter in accordance with the present invention.

FIG. 13 depicts a fourth illustrative embodiment of a tunable filter in accordance with the present invention.

FIG. 14 depicts a fifth illustrative embodiment of a tunable filter in accordance with the present invention.

FIG. 15 depicts the operation of the tunable filter of FIGS. 10 and 11.

Detailed Description

FIG. 2a depicts a block diagram of a tunable filter **200** in accordance with the present invention. Tunable filter **200** comprises optical cavity **210**, tuning device **220** and filter-disabling device **230**.

The length of the optical (resonant) cavity **210** determines the center transmission wavelength of tunable filter **200**. Tuning device **220** is operable to change the center transmission

wavelength of tunable filter **200**. To do so, tuning device **220** varies a parameter (*e.g.*, cavity length, *etc.*) that is determinative of the center transmission wavelength.

Filter-disabling device **230** is operable to temporarily disable the transmission behavior of the filter by disrupting the finesse or transmission characteristic of optical cavity **210**. Though depicted as separate elements in FIG. 2a, in some embodiments, tuning device **220** and filter-disabling device **230** are realized by a single element.

Tunable filter **200** is advantageously operated in accordance with illustrative method **250** depicted in FIG. 2b. By doing so, tunable filter **200** operates in a "hitless" manner, wherein it does not transmit or "hit" any undesired intervening channels during tuning, even though such channels are not otherwise interrupted.

In accordance with operation **252** of method **250**, the finesse of optical cavity **210** is disrupted so that optical signals are not transmitted by filter **200**, regardless of their wavelength. This is done by enabling filter-disabling device **230**. In operation **254**, tunable filter **200** is tuned using tuning device **220**. After tunable filter **200** is tuned to the desired center transmission wavelength, finesse is recovered by disabling filter-disabling device **230**, in accordance with operation **256**.

In use as a drop filter or an add/drop filter, waveguides (not shown in FIG. 2a) are of course placed in optical communication with tunable filter **200** to effect that function. Several specific embodiments of a tunable add-drop filter in accordance with foregoing description are now described.

FIGS. 3a, 4a, 5a and 6a depict an illustrative embodiment of tunable filter **200** and the operation thereof in accordance with illustrative method **250**. In the embodiment depicted in FIGS. 3a, 4a, 5a and 6a, tunable filter **200** is configured in the manner of the tunable Fabry-Perot etalon add-drop switch of FIG. 1b. Unlike the switch of FIG. 1b however, tunable filter **200** advantageously includes a filter-disabling device.

In more detail, tunable filter **200** of FIGS. 3a, 4a, 5a and 6a, in its implementation as an add-drop filter, has two spaced-apart mirrors **310** and **312**, two lenses **306** and **308**, input waveguide **302**, output waveguide **304**, add waveguide **314** and drop waveguide **316**, arranged as shown.

Spaced-apart mirrors **310** and **312** define an optical cavity. Mirror **310** is "fixed" (*i.e.*, non-movable) while mirror **312** is movable. In the depicted embodiment, mirror **312** is advantageously capable of "tilting" or being rotated relative to fixed mirror **310**, in addition to

being "translatable" (*i.e.*, non-rotational movement) to vary the spacing between the mirrors (*i.e.*, to vary the cavity length). As described further below, by virtue of such functionality, mirror **312** serves as both tuning device **220** and filter-disabling device **230**.

Lens **306** is operative to receive an optical signal from input waveguide **302** and to collimate it. Lens **306** is also operative to receive a collimated optical signal reflected by/transmitted through mirror **310** and focus it into output waveguide **304**. Similarly, lens **308** is operable to receive a collimated optical signal reflected by/transmitted through mirror **312** and focus it into drop waveguide **316**, and to receive an optical signal from add waveguide **314** and to collimate it. Ray tracings depict the path of optical signals through tunable filter **200** as described above. Lenses **306** and **308** can be, without limitation, a graded index (GRIN) lens, a ball lens and a molded (*e.g.*, injection molded) lens.

For pedagogical purposes, it is assumed for the following description that a multiplexed optical signal is delivered to tunable filter **200** by input waveguide **302**. The multiplexed optical signal consists of five channels, each characterized by a different peak wavelength.

FIG. 3a depicts tunable filter **200** in a specific state, wherein mirrors **310** and **312** are parallel to one another and are separated by gap $\mathbf{G_1}$ (*i.e.*, $\mathbf{G_1}$ is the length of optical cavity). In the state illustrated in FIG. 3a, tunable filter **200** is assumed to reflect channels 1-3 and 5 and to transmit channel 4, as illustrated by the plots of FIGS. 3b and 3c.

Given the foregoing assumptions, in the state depicted in FIG. 3a, channel 4 is transmitted through mirror **312** to lens **308**, which focuses channel 4 into drop waveguide **316**. The multiplexed signal, without channel 4, is reflected by the optical cavity to lens **306**, which focuses the signal into output waveguide **304**. A signal having the same peak wavelength as channel 4 can be added to reflected channels 1-3 and 5 via add waveguide **314**.

As will be appreciated by those skilled in the art, in some embodiments, an "add" waveguide (*e.g.*, add waveguide **314**) is not present, so that the filter is simply a "drop" filter. The "add" functionality can be provided elsewhere in the optical communications network, or not at all, as appropriate. In still other embodiments, a "drop" waveguide is not present. Rather, the passed signal is transmitted directly to an optical device, such as a detector.

FIGS. 4a – 6a depict, collectively, "hitless" tuning of tunable filter **200** in accordance with method **250**. In particular, those Figures show how tunable filter **200** is tuned to a new center transmission wavelength (*e.g.*, wherein channel 2 is transmitted and channels 1 and 3-5 are reflected) while none of the intervening channels are transmitted.

In accordance with operation **252** of method **250**, before tuning filter **200** to a new center transmission wavelength, finesse is disrupted. To do so, the filter-disabling device is enabled. In the context of the present embodiment, the filter-disabling device is enabled by tilting mirror **312** so that mirrors **310** and **312** are no longer parallel to one another. FIG. 4b depicts the filter-disabling device enabled wherein mirror **312** is "tilted" or "rotated" along path **TL**.

FIGS. 4b and 4c illustrate the effect that tilting mirror **312** has on the finesse of the optical cavity. In particular, the cavity becomes substantially completely reflective to all wavelengths (*e.g.*, channels 1-5).

In accordance with operation **254** of method **250**, after disabling the filter, it is tuned to a desired center transmission wavelength. In the context of the present invention, filter **200** is tuned by *translating* mirror **312**, thereby changing the gap between mirrors **310** and **312** (*i.e.*, the length of the optical cavity). The *tilt* of mirror **312** is maintained during translation thereby ensuring that filter **200** does not transmit undesired intervening channels during the tuning operation. FIG. 5a depicts the gap between mirrors **310** and **312** being increased as mirror **312** is translated along path **TR**.

FIGS. 5b and 5c show that filter **200** remains disabled wherein channels 1-5 are substantially completely reflected.

In accordance with operation **256** of method **250**, after tuning to the desired center wavelength, finesse is recovered. To do so, the filter-disabling device is disabled. In the context of the present invention, the filter-disabling device is disabled by returning mirror **312** to its "original" non-tilted orientation so that mirrors **310** and **312** are once again parallel. FIG. 6a depicts mirror **312** rotated, along path **DTL**, to its non-tilted orientation, and further depicts mirrors **310** and **312** separated by gap $\mathbf{G_2}$ (different in size from gap $\mathbf{G_1}$). Since mirrors **310** and **312** are returned to a parallel disposition, the transmission characteristic of filter **200** is again exhibited. With mirrors **310** and **312** separated by gap $\mathbf{G_2}$, filter **200** is tuned to a different center transmission wavelength than when the mirrors were separated by gap $\mathbf{G_1}$. (Compare FIGS. 6b and 6c showing transmission of channel 2 and reflection of channels 1 and 3-5 with FIGS. 3b and 3c showing transmission of channel 4 and reflection of channels 1-3 and 5.)

It will be appreciated that the "translation" and "tilting" functionality of mirror **312** can be implemented using any one of a variety of different structural arrangements. One such arrangement is depicted in FIGS. 7, 8 and 9a – 9c.

FIG. 7 (top view) and FIG. 8 (side view along line **1-1** of FIG. 7) depict an illustrative embodiment of translatable and tiltable mirror **312**. Translatable/tiltable mirror **312** comprises mirror **708** disposed on layer **706**. Though depicted as a single layer, mirror **708** is advantageously realized as a dielectric mirror, well known in the art, comprising multiple layers of material(s) wherein the refractive indices of adjacent layers are different. Supports **804** suspend layer **706** above substrate **702**, forming gap **714** therebetween. Two independently controllable electrodes **710** and **712** are disposed on layer **706** flanking mirror **708**.

In operation, a voltage applied across one or both electrodes **710**, **712** (and substrate **716**) generates an electrostatic force that attracts the layer **706**, and mirror **708**, toward substrate **716**. Applying voltage unequally to electrodes **710** and **712** imparts a controllable angle (*i.e.*, tilt or rotation) to layer **706** and, hence, mirror **708**. (*See* FIG. 9b.) In such a manner, movable mirror **312** functions as the filter-disabling device, disrupting the finesse of the optical cavity by destroying the parallel relationship of the two mirrors that define the optical cavity.

Once the tilted disposition of mirror **312** is established, translation of the mirror is effected, as required, by increasing the voltage (but maintaining an imbalance of applied voltage as between the two electrodes). In this manner, a "tilt" is maintained, but layer **706** is drawn closer to substrate **716**. To recover the finesse of the optical cavity, the voltage of the appropriate electrode is increased until layer **706** is rotated back to a non-tilted orientation. (*See* FIG. 9c). For additional information pertaining to electrically-controlled "tilt" mirrors, see U.S. Pat. App. Serial No. 09/271,577, which is incorporated by reference herein.

In an embodiment depicted in FIG. 8, fixed mirror **718** is disposed on back surface **717** of substrate **716** to create the optical cavity. Alternatively, in the embodiment depicted in FIGS. 9a – 9c, fixed mirror **918** is fabricated as part of a separate multi-layer structure that includes substrate **916**. As desired or necessary, a window **719** is formed within the substrate (*e.g.*, substrate **716** of FIG. 7). Window **719** is required, for example, if substrate **716** is not optically transparent at the operating wavelengths of filter **200**.

Tunable filter **200** is fabricated in well-known fashion using standard micro-machining techniques and devices.

When in use as an add-drop filter in an optical communications system, the embodiments of tunable filter **200** described in this Specification incorporate various waveguides (*e.g.*, optical fibers, *etc.*) and lenses for effecting communication with the communications system and subscriber terminals. (*See*, for example, FIG. 3a – 6a.) Such waveguides and lenses are not

shown in conjunction with the various embodiments of tunable filter **200** so that attention is focused on elements that are germane to an understanding of the present invention. Those skilled in the art will know how use waveguides and lenses in conjunction with tunable filter **200**.

FIGS. 10 and 11 depict yet another embodiment of a tunable filter **200** in accordance with the present teachings. More particularly, FIG. 10 depicts the overall structure of tunable filter **200** and FIG. 11 provides additional detail concerning the structure of the mirrors that define the optical cavity of the tunable filter.

Like the previously described embodiments of tunable filter **200**, the embodiment depicted in FIG. 10 includes an optical cavity, tuning device and filter-disabling device. Such elements are, however, implemented in a different manner than for the translatable, tilting mirror filter previously described.

In the embodiment illustrated in FIG. 10, tunable filter **200** includes substrate **1002**, fixed mirror **1016** and movable mirror **1008**, arranged as shown. Movable mirror **1008** is suspended above fixed mirror **1016** by supports **1004** such that a primary gap **PG** is defined therebetween.

Movable mirror **1008** is bifurcated into two groups of layer(s) **1010** and **1012**. Each group of layer(s) comprises at least one layer. Layer(s) **1012**, hereinafter referred to as "the upper movable layer," is suspended over layer(s) **1010**, hereinafter referred to as "the lower movable layer," by supports **1006** defining auxiliary gap **AG** therebetween.

Like movable mirror **312** previously-described, movable mirror **1008** functions as both the tuning device and the filter-disabling device. Such dual functionality is achieved, however, in a different manner by virtue of the differences in structure of those mirrors. In particular, as described further below, rather than tilting mirror **1008** to disrupt the finesse of the optical cavity, the size of auxiliary gap **AG** is changed, which achieves the same result. Note, however, that in both such cases, finesse is disrupted by altering the reflectivity, *along the optical axis*, of (at least) one of the two mirrors that define the optical cavity.

Regarding the structure of the mirrors, movable mirror **1008** is advantageously divided into layers of material that are an odd-multiple of an eighth of a wavelength (of the optical signal) thick (as measured in the layer). For example, in the embodiment depicted in FIG. 11, upper layer **1012** comprises a layer **1116** of material that has a thickness of five-eighths of a wavelength. Bottom layer **1010** comprises three layers of material including a layer **1110** that has a thickness of one-quarter of a wavelength, a layer **1112** that has a thickness of one-quarter of a wavelength and a layer **1114** that has a thickness of one-eighth of a wavelength.

By virtue of the overall thickness of movable mirror **1008** (5/4 wavelengths plus the gap), the finesse of illustrative tunable filter **200** of FIGS. 10 and 11 is at a maximum when auxiliary gap **AG** is equal to an integer number of one-half wavelengths. As auxiliary gap **AG** changes, the finesse is disrupted. In this manner, the filter-disabling device is implemented. Changing primary gap **PG** (*i.e.*, changing the optical cavity defined between opposed surfaces of layers **1110** and **1108**) changes the center transmission wavelength of the filter and, as such, implements the tuning function. Since upper and lower movable layers **1012** and **1010** of movable mirror **1008** are independently movable, auxiliary gap **AG** can be changed independently of primary gap **PG** to some extent. Note, however, that changes in the auxiliary gap **AG** affect tuning and changes in the primary gap affect finesse.

FIG. 15 depicts the operation (theoretical) of illustrative tunable filter **200** of FIGS. 10 and 11 based on values of the primary and the auxiliary gap for states A – J listed in TABLE 1 below.

TABLE 1

		----Auxiliary Gap-----		-----Primary Gap-----	
State	Operating λ (nm)	Angstroms	Fract λ	Angstroms	Fract λ
A	1550	7750	0.500	15,500	1.000
	1565	7750	0.495	15,500	0.990
B	1550	7300	0.471	15,550	1.003
	1565	7300	0.467	15,550	0.994
C	1550	6700	0.432	15,600	1.007
	1565	6700	0.428	15,600	0.997
D	1550	5600	0.361	15,650	1.010
	1565	5600	0.358	15,650	1.000
E	1550	5600	0.361	15,700	1.013
	1565	5600	0.358	15,700	1.003

TABLE 1, cont'd.

Identifier	Operating λ (nm)	----Auxiliary Gap----- Angstroms	Fract λ	-----Primary Gap----- Angstroms	Fract λ
F	1550	5600	0.361	15,800	1.019
	1565	5600	0.358	15,800	1.010
G	1550	5600	0.361	15,850	1.023
	1565	5600	0.358	15,850	1.013
H	1550	6650	0.429	15,800	1.019
	1565	6650	0.425	15,800	1.010
I	1550	7300	0.471	15,750	1.016
	1565	7300	0.467	15,750	1.006
J	1550	7825	0.505	15,700	1.013
	1565	7825	0.500	15,700	1.003

Referring to FIG. 15 and TABLE 1 above, at state **A**, tunable filter **200** exhibits strong notch filter characteristics (*i.e.*, high Q) at a passband having a center transmission wavelength of about 1550 nm. As auxiliary gap **AG** is changed from λ/2 as indicated at states **B**, **C** and **D**, the finesse of the optical cavity is disrupted. As shown in FIG. 15, the transmissibility of the filter falls off sharply with the movements indicated proceeding from state **A** to **B** to **C** to **D**.

With finesse suitably low at state **D**, the auxiliary gap **AG** is maintained at 5600 angstroms while primary gap **PG** is increased as indicated at states **E**, **F** and **G**. From state **G**, auxiliary gap **AG** is then sequentially increased to λ/2 at final state **J**. Primary gap **PG** is decreased from its value at state **G** to its final value at state **J**. At state **J**, tunable filter **200** exhibits high Q at a passband having a center transmission wavelength of about 1565 nm.

Thus, in proceeding from state **A** to state **J**, tunable filter **200** is tuned to a new center transmission wavelength in accordance with method **250**, wherein:

- in a first operation **252** (implemented by the sequential decrease in auxiliary gap **AG** from λ/2), finesse is disrupted (by enabling the filter-disabling device);
- in a second operation **254** (implemented by the sequential increase in primary gap **PG**), the filter is tuned; and

- in a third operation **256** (implemented by the sequential increase in auxiliary gap **AG** back to $\lambda/2$), finesse is recovered (by disabling the filter-disabling device).

It will be understood by those skilled in the art that primary gap **GP** was increased to a maximum at state **G**, then *decreased* from state **G** to final state **J** to keep the finesse suitably low during the tuning operation. In other words, if auxiliary gap **AG** is increased to 7825 angstroms ($\lambda/2$ at the new center transmission wavelength) from state **E** (**AG** = 5600 angstroms, **PG** = 15,700 angstroms), finesse begins recovering (*i.e.*, transmissibility increases) before the new center transmission wavelength at 1565 nm is established. It is within the capabilities of those skilled in the art to calculate finesse and center transmission wavelength as a function of auxiliary gap size, primary gap (optical cavity) size and mirror specifics to determine preferred tuning routes.

FIG. 12 depicts a further embodiment a tunable filter **200** in accordance with the illustrated embodiment of the present invention. Tunable filter **200** depicted in FIG. 12 is a Fabry-Perot etalon comprising two dielectric mirrors **1208** and **1218** that define an optical cavity having a size or gap **G12**. Mirror **1208** is configured as a movable mirror. In particular, dielectric layers **1208** are disposed on a layer **1206** that is supported, via supports **1204**, over substrate **1202**. As a voltage is applied across layer **1206** and substrate **1202** (which are suitably conductive or include electrodes, *etc.*), the resulting electrostatic force draws layer **1206** and mirror **1208** toward substrate **1202**. In such a manner, the size of the optical cavity can be varied so that the filter can be tuned.

Tunable filter **200** of FIG. 12 also includes electrically-switched absorbing, scattering or depolarizing media **1210** that is disposed within the optical cavity. Media **1210** functions as the filter-disabling device. Under applied voltage, such as from controlled voltage source **1212**, media **1210** changes from being transparent at the operating wavelengths to being opaque or reflecting (or visa-versa). Thus, assuming a multiplexed signal is entering filter **200** through mirror **1208**, when media **1210** is transparent, the notch filter transmission characteristic is unaffected and signals that are within the passband are transmitted through the media and mirror **1218**. When, however, media **1210** is opaque to optical signals, such signals can not be transmitted through the filter even if they are within the passband of the filter. Suitable electrically-switched absorbing media include, without limitation, a quantum well modulator. Suitable electrically-switched scattering and depolarizing media include, without limitation, liquid crystal material.

In the various embodiments described above, one of the mirrors that defines the optical cavity is suspended, or is disposed on a suspended layer, so that the mirror is movable on application of a voltage across the layer and a substrate. To apply a voltage, the layer or mirror and the substrate must include electrically-conductive electrodes (*e.g.*, metallized regions) or comprise an electrically conductive material (polysilicon) or comprise a material that can be rendered suitably conductive via dopants (boron, *etc.*).

Moreover, a movable mirror must be robust as it is subjected to various mechanical stresses. To that end, the movable mirror advantageously incorporates a layer of silicon nitride. As is well known, the stress/mechanical strength of silicon nitride can be tailored during its deposition/growth. Thus, in one embodiment, movable mirror **1008** depicted in FIG. 10 is configured as follows: layers **1116, 1114** and **1110** comprise polysilicon, and layer **1112** comprises silicon nitride. The fixed (*i.e.*, non-moving) mirror also advantageously comprises layers of polysilicon and silicon nitride. If the optical signal must pass through the substrate, then the substrate must be optically transparent at the operating wavelengths of the filter. Silicon and gallium arsenide, for example, are suitably transparent at communications wavelengths.

FIG. 13 depicts an additional embodiment of a tunable filter in accordance with the present teachings. Tunable filter **200** depicted in FIG. 13 includes two spaced-apart mirrors **1308** and **1304** that define an optical cavity. Mirror **1308** is disposed on substrate **1312** and mirror **1304** is disposed on substrate **1302**. Antireflection coating **1306** is advantageously disposed on substrate **1302**. Adjacent to mirror **1308** and within the optical cavity is electrically switched **1210**. Controlled voltage source **1314** is electrically connected to media **1210**. A gap **G13** separates media **1210** from mirror **1304**. The tunable filter also includes heater **1316**.

In operation, illustrative filter **200** of FIG. 13 is tuned by activating heater **1316** so that substrate **1312** is heated and expands. The expansion of substrate **1312** decreases the size of the optical cavity (*i.e.*, mirror **1308** moves closer to mirror **1304**) effecting the tuning function. Electrically switched media **1210** again functions as the filter-disabling device and is used in the manner previously described.

FIG. 14 depicts a final illustrative embodiment of a tunable filter **200** in accordance with the present teachings. As in the previous embodiments, the tunable filter of FIG. 14 includes an optical cavity, tuning device and a filter-disabling device. Such elements are, however, configured somewhat differently in the present embodiment as compared with previously-described embodiments.

Tunable filter **200** comprises ring resonator **1404**, adjustable delay device **1412** and adjustable loss device **1416**, arranged as shown. Multiplexed optical signal $\boldsymbol{m\text{-}\lambda}$ is delivered over waveguide **1402** to ring resonator **1404** via one-percent coupler **1410**. Dropped signal $\boldsymbol{\lambda_i}$ is removed from the filter **200** via one-percent coupler **1414** over "drop" waveguide **1408**. Similarly, a signal having wavelength $\boldsymbol{\lambda_i}$ identical to the dropped signal can be added over "add" waveguide **1406** via one-percent coupler **1414**.

In operation, coupler **1410** couples about one percent of multiplexed optical signal $\boldsymbol{m\text{-}\lambda}$ to ring resonator **1404**. The ring resonator, which is a waveguide configured in circular fashion as depicted in FIG. 14, defines an optical cavity. The resonance of ring resonator **1404** (*i.e.*, the passband of the filter) is a function of its length (*i.e.*, the length of the optical cavity). An optical signal within the passband of the filter is coupled, via coupler **1414,** to drop waveguide **1408**.

As in previous embodiments, the filter is tuned by changing the size of the optical cavity. In the present embodiment, this is done using adjustable delay device **1412**. In one embodiment, the adjustable delay device is implemented electro-optically wherein the index of refraction of a portion of the ring resonator is changed by altering a voltage applied thereto. Changing the index of refraction changes the effective cavity length and hence tunes the cavity. In another embodiment, the adjustable delay device is implemented thermo-optically, wherein a current heats ring resonator **1404,** causing an increase in cavity length.

Filter **200** depicted in FIG. 14 is disabled while tuning using adjustable loss device **1416**. The adjustable loss device can be implemented, for example, as a semiconductor optical amplifier. The semiconductor optical amplifier, which can be, for example, indium-gallium-arsenide, can be coupled in-line with ring resonator **1404**. In the absence of current, the semiconductor optical amplifier is opaque. With an appropriate amount of applied current, the optical amplifier becomes transmissible. Adjustable loss device **1416** thus functions as the filter-disabling device.

It is to be understood that the above-described embodiments are merely illustrative of the invention and that many variations can be devised by those skilled in the art without departing from the scope of the invention. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.